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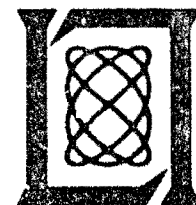
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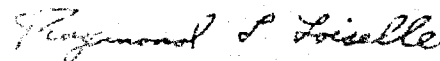
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FOR THE COMMANDER

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LINCOLN LABORATORY

BASELINE LINK CALCULATION
FOR OPTICAL BROADCASTING THROUGH WATER

R. M. LERNER

Division 6

TECHNICAL NOTE 1977-28

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LEXINGTON   MASSACHUSETTS

ABSTRACT

A link calculation is carried out to determine whether present blue-green technology can support wide-area broadcasting from satellite to oceanic underwater receivers at bit-per-second rates; and to determine what improvements, beyond the status of technology assumed, would be most productive in making such broadcasting possible. The link technology today is tens of dB away from supporting a wide-area broadcast service; the most productive direction for developmental technology is in producing a suitable, efficient laser source with one hundred watts or more of average power output.

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I.   INTRODUCTION

The requirements for a satellite communication system can be divided into
two categories. Into the first fall the link hardware and propagation
characteristics (transmitter, path, receiver). Into the second fall the
overall requirements (coverage, rates, coding strategies), etc., in which the
link is embedded. The link will support, or fail to support, these overall
requirements according to the state of link technology.

This is a first-cut evaluation of the state of optical link technology
to support an overall objective to broadcast to substantial fractions of the
ocean surface, through the blue-green window in water transmission, to a
receiver at depth. We make use of two model links shown in Fig. 1: a base-
line laser link, and a classical heliograph. For convenience in comparing
the two approaches, the heliograph uses the same aperture as is used to power
the solar cell array in the laser system spacecraft. While the performance
of the laser system does indeed represent the writer's opinion of the state-
of-the-art, its purpose is to provide a standard against which to evaluate
possible improvements in the technology. The heliograph is included to hold
any "high technology" link to a standard of what can be done by "simply"
redirecting the sunlight that falls on the solar cell array.

Without entering into detailed system requirements, we take it as
given that we wish to be able to broadcast to roughly 10^{13} m^2 (130 dB m^2) of
surface at rates of the order of 1 bit/sec; and that we wish to operate the
receiver at sufficient depth underwater so that all of the light collected
is thoroughly scattered in direction-of-arrival. It turns out that with
these constraints, available transmitter average power output is a critical
factor, as is the multipath dispersion of sea (and clouds, if present).
There also turns out to be a tradeoff between rate and area covered. Thus,
for a given collection of other constraints, it makes sense to plot rate-
coverage area product as a function of solar cell (or heliograph) collection
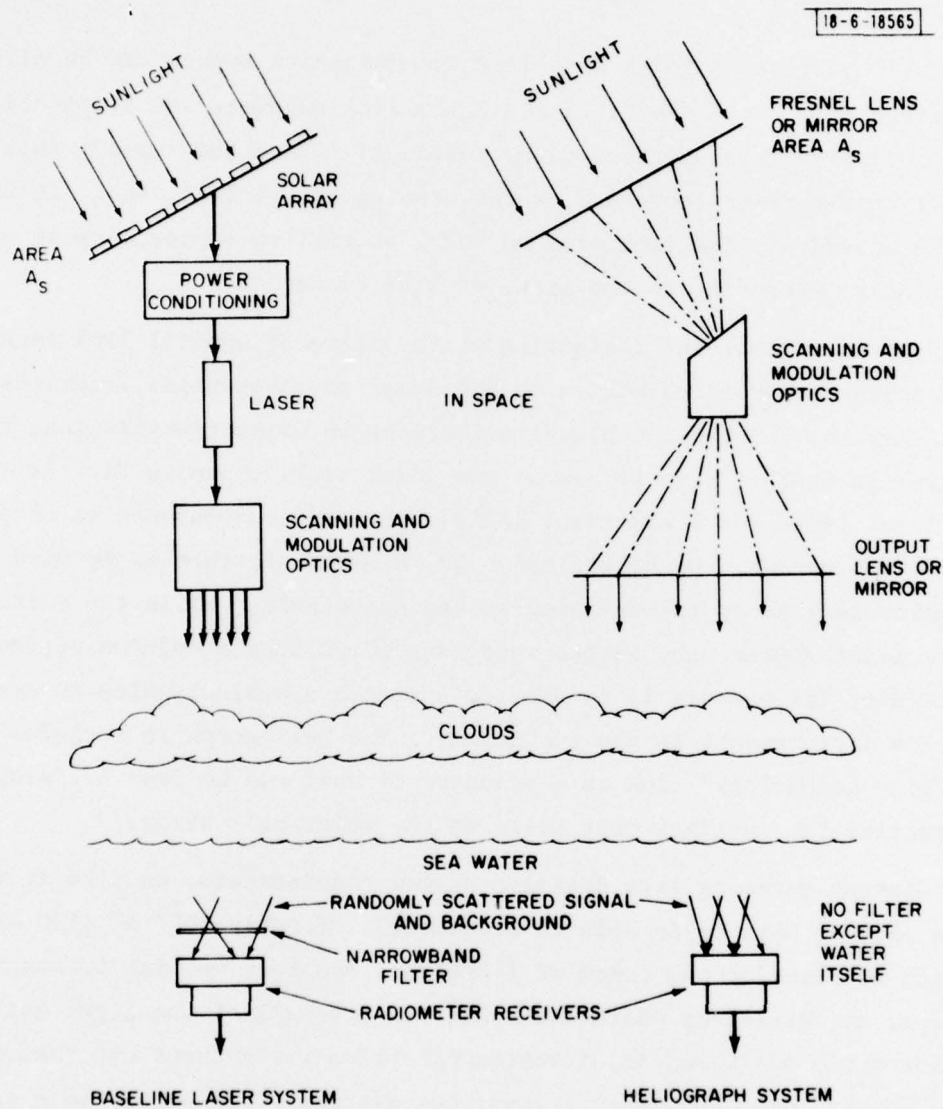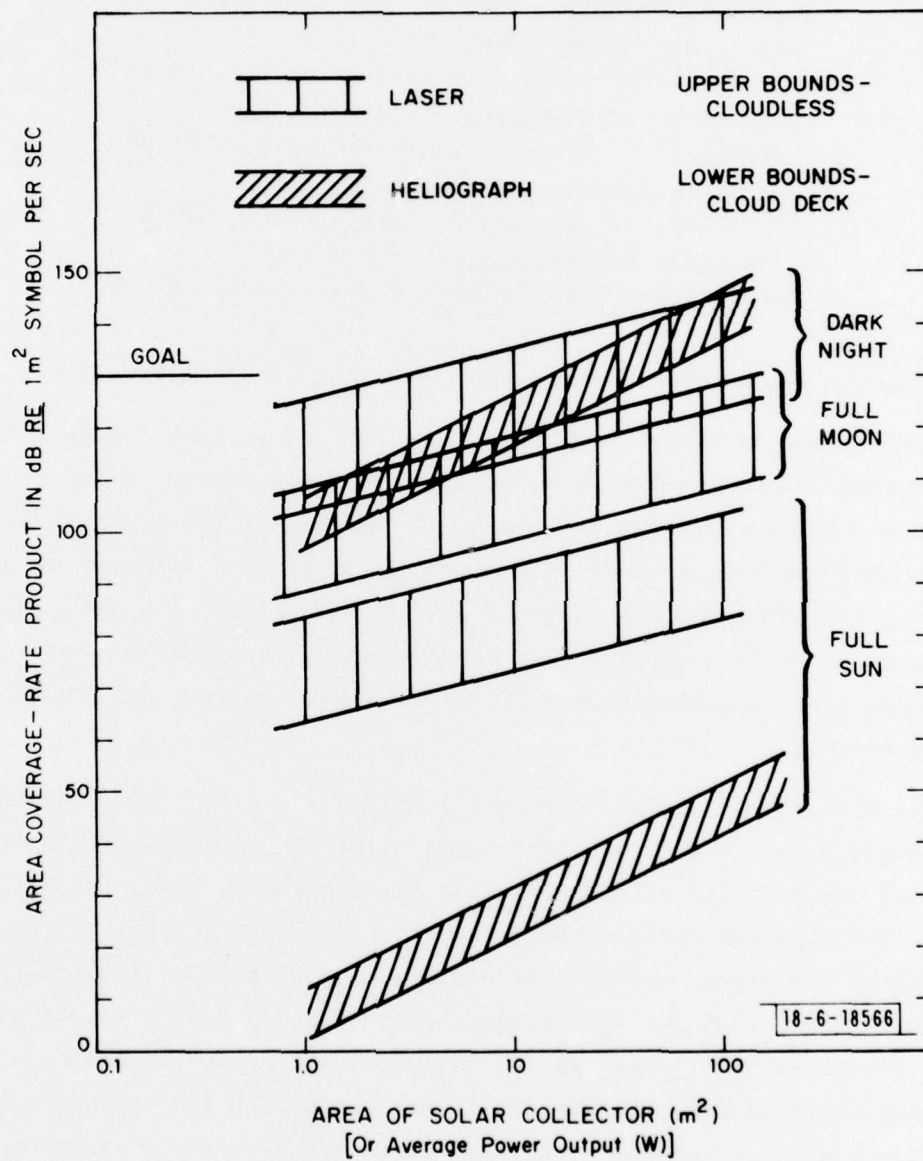aperture. This is done in Fig. 2, where the following assumptions have been
made:

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18-6-18565

Fig. 1. Baseline links.

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Fig. 2. Link performance.

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Receiving Aperture........................ 1 m^2

Irradiance Attenuation
Surface-to-Depth....................... 30 dB

Additional Attenuation
due to Clouds.......................... 10 dB

Engineering Performance
Margins................................ 25 dB

Available Receiver Filter
Bandwidth.............................100 Å

Efficiency of Conversion
Sunlight-to-Laser-Output............... 0.001

Other factors which enter the calculation of Fig. 2 are given later.

Performance in Fig. 2 is given as the product of rate (symbols/sec) and area covered. The abscissa is the number of square meters of solar cells devoted to making power for the laser. To within the accuracy of Fig. 2, the abscissa can also be read as watts of laser power.* Performance bounds are given for three interference conditions: dark night skyglow, full moonlight, and full sunlight. The upper bound of each performance region represents clear sky conditions; the lower bound, an overcast sky with clouds several km thick.

The wide limits on the performance between cloudless and overcast sky are a consequence of a 30 dB increase in multipath spreading (from 10^{-7} to 10^{-4} sec) coupled with a 10 dB increase in propagation loss, for a total of 40 dB. Both factors enter ultimate system performance as the square root, for a total performance difference of 20 dB. A heliograph limited to the angular dispersion of sunlight cannot, from an assumed synchronous altitude, take full advantage of even the 10^{-4} dispersion time of the clouds. Being duty-cycle limited, the performance of the heliograph is square-law with available power, and linear with those factors that enter dispersion-limited performance as the square root.

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*Reflecting the assumed conversion efficiency of solar power to laser power of 10^{-3}.

We observe from the figure that on a dark night, with apertures similar to those used for the communication antenna on ATS-F, the heliograph is (in principle) able to function now in the ballpark of the desired 130 dB rate-coverage product. In full sun on an overcast day, the present laser technology of the 405B program (a few tenths of a watt of satellite-supportable green light) is over 70 dB away from usefulness.

Roughly interpreting the horizontal scale in Fig. 2 as watts of narrow band light, it is not prejudging the possibilities for other technical improvement to state that even as a clear-weather broadcast system, there is no serious prospect of feasibility until an average transmitter power of 100W can be achieved.

Our calculations make extensive use of a dB power scale. The optical receiver used contains a square law device, which introduces the possibility of confusion in the form of a factor of two between dB levels on the input and output sides of the detector. The reader should note that the dB scale used here is always referred to the optical power side of the detector; and that numbers of (energy) events and ratios, K, are converted to dB as 10 log K.

II. PHOTON-COUNTING RECEIVER THEORY

In all cases of interest to us, the optical background light exceeds other sources of noise, even after all possible filtering has been done. The receiver functions as a radiometer, ideally one which counts individual photoelectric events.

The simplest form of such a receiver (stripped of initial filters and field stops) is shown in Fig. 3. Ideally, if an incident flux of P watts/m^2 falls on a receiver area of A_R m^2, there will be M counts per second.

$$M = PA_R \eta /h\nu \tag{1}$$

where η is the efficiency of the receiver (at most unity); and $h\nu$ is the energy of the photon, roughly 4×10^{-19} Joule at green light.

If P_N is the background noise flux, in time τ one counts N events

$$N = P_N A_R \tau \eta/h\nu \tag{2}$$

If P_S is the signal power during the counting interval, the number of signal counts is

$$S = P_S A_R \tau \eta/h\nu \tag{3}$$

Unlike the background, the signal can be pulsed (by some combination of pulsing the transmitter and utilizing the dwell time of the footprint of a scanned narrow beam) while holding the symbol energy flux, $P_S \tau$, constant. Thus, by choosing τ ever shorter, holding S constant, we can reach the situation in which S is greater than N. The practical lower limit to τ is not laser technology (which can produce 10^{-12} sec pulses) but the multipath dispersion, τ_m, of the propagation medium.

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AREA A

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INCIDENT
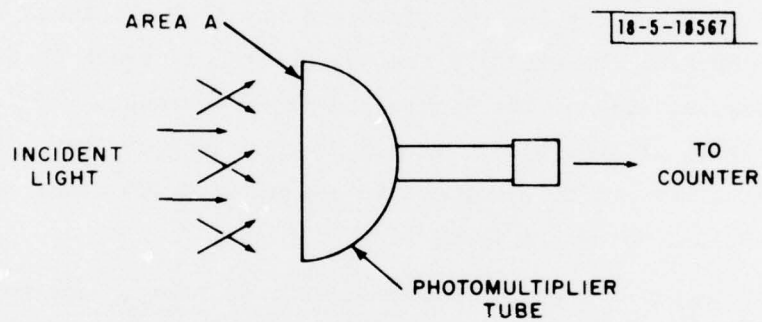LIGHT

TO
COUNTER

PHOTOMULTIPLIER
TUBE

Fig. 3. Simple receiver.

On both practical and theoretical grounds, the multipath in an attenuating medium such as water is the lesser of depth or attenuation length, converted to seconds of propagation time.

As a practical matter, under water, τ_m is of the order of 10^{-7} sec.

Few controlled measurements of the multipath dispersion of clouds have been undertaken. Light diffuses through clouds thick enough to continuously extinguish an image of the sun. Both experiment and theory suggest a dispersion time roughly 5 to 10 times the physical thickness of the cloud deck when the sunlight reaching the surface is one tenth of full sunlight (a typical overcast day). This leaves undefined the total thickness of the overcast, which is generally measured in thousands of feet. The overcast cloud multipath τ_c, lies somewhere in range 10 to 100 μsec. We have conservatively assumed the latter.

On the basis of theory and experiment, we take τ_m due to the water to be of the order of 10^{-7} sec, τ_m for overcast-type cloud cover to range up to 10^{-4} sec.

The value of τ_m places a floor under the payoff for short-signal pulsing; we obtain

$$N = P_N \, A_R \eta \tau_m / h\nu \tag{4}$$

Suppose that there is available W_D average watts at depth, to be used to produce R pulses per second at any one of a possible set of receivers which are distributed over a surface area of σ_G m^2. The average energy available for each pulse decision is thus

$$\tau_m \, P_S = W_D / (\sigma_G R) \tag{5}$$

or, in terms of the signal count S

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$$S = \eta W_D \, A_R / (\sigma_G R h \nu) \tag{6}$$

Observe that this result is independent of the particular means by which the signal pulses (P_S, τ_m) were actually delivered to the receiver. At one extreme, W_D could be broadcast to the entire area σ_G at once, using pulses with a duty cycle $\tau_m R$ and a peak power $W_D / \tau_m R$. At the other extreme, one could scan across σ_G a time-continuous beam of W_G watts, whose footprint is restricted to a suitably small fraction of σ_G, so that the dwell time at any receiver site is τ_m.

Let the count due to background be n_i during the ith interval of duration τ_m. Suppose that we have added knowledge that the <u>average</u> count during this interval is N_i. Then, $(n_i - N_i)$ is a random variable, which can be assumed to be gaussianly distributed with a standard deviation $\sqrt{N_i}$ if N_i is large enough. Reliable signal decisions can be made if

$$S > Q \sqrt{N_i} \tag{7}$$

where Q is a factor generally called the "detection margin".[*]

For this "radiometer" scheme to work, N_i must itself be known to within $\sqrt{N_i}$. One method for doing so is to average the counts n_k over several adjacent time intervals.

$$N_i = \text{ave} \{n_k\} \tag{8}$$

The possibility of doing so depends on the stability of N over time spans comparable with τ_m, in spite of possible variations induced by fluctuation

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[*] For low S/N_i, Q is typically in the range 5 to 10 for symbol error probabilities of the order of 10^{-4}, without coding for further error reduction. See E. A. Bucher, "Error Performance Bounds for Two Receivers for Optical Communication and Detection," Appl. Opt., <u>11</u>, 887, (1972). Note that Bucher uses $S\tau$ for our S.

of the sea surface, or of the cloud cover. While this assumption of stability of N appears reasonable, on physical grounds, for a time span of 1 μsec (for τ_m caused by the water) it needs to be established also for time spans of 1 ms (for τ_m caused by clouds).

Inasmuch as the possibility of detection depends on $S/\sqrt{N}$, those factors which affect N alone, or S and N equally, will enter the performance only as the square root. In general, the only factors which enter without the square root are the average signal power, the rate, and the coverage.

This fact is emphasized by combining Eqs. (4), (6) and (7) to set

$$R \, \sigma_G \leq \frac{W_D}{Q} \sqrt{\frac{\eta \, A_R}{h\nu \, P_N \, \tau_m}} \tag{9}$$

With the role of Q expanded to include all engineering performance margins, and with the role of η expanded to include all transmission losses suffered equally by signal and background, the form of Eq. (9) is the one used in Appendix C to calculate the performance curves of Fig. 2.

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III. THE COMPARISON HELIOGRAPH

Satellites are, by and large, powered from solar collectors. If the electricity from such collection systems is used to power high technology light sources, such as lasers, the overall efficiency is abysmally low. The state-of-the-art is of the order of magnitude 1 watt of signal output for a kilowatt of sun.

The low sunlight-to-signal conversion efficiency invites comparison with a "low-technology" baseline system, a heliograph, in which a similar amount of sunlight is redirected at the earth. We find, in Appendix A, that for each kilowatt of incident sunlight, roughly 125 watts may by useful in the blue-green window of the water. The high technology advantages of the laser are principally those which enter the performance Eq. (9) as the square root. These include achieving received pulses as short as τ_m and lowering interference P_N through the use of narrowband filtering. With the low overall power efficiency of the laser, some 40 dB of advantages which enter performance as the square root must be spent in catching up with the 20 dB more powerful heliograph.

Thus it makes sense to always check the performance of an indirect signalling system such as the laser against that of the heliograph which redirects the sunlight falling on the required solar cell array. We assume that the heliograph is limited in narrowness of beam to the angular sub-tense of the sun. (In principle, one could improve matters by using even larger optics to form the earth-pointing part of the beam; but given this larger optics, the best use is to gather more sunlight.) because of this limitation, geometric factors limit the dwell time of a heliograph pulse to a duty cycle greater than

$$\zeta < \Omega_s \, r_o^{\,2} / \sigma_G \qquad\qquad (10)$$

where Ω_s is the angular subtense of the sun (10^{-4} sr) and r_o is the slant

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range to the satellite. For synchronous satellites with r_o^2/σ_G, about 100, ξ is roughly 10^{-2}, which is substantially worse than what is required to fully exploit the τ_m of clouds or sea.

The actual integration time for the heliograph is ξ/R. Thus, the integration time depends on the $R\sigma_G$ product

$$\tau = \Omega_S \, r_o^2/R\sigma_G \tag{11}$$

if the value of τ so calculated is greater than τ_m. A further limit on the validity of Eq. (10) is that ξ as given by Eq. (8) cannot exceed unity.

Within these constraints we find

$$R\sigma_G = \frac{W_D^2}{Q^2} \, \frac{\eta}{P_N \, \Omega_S \, \eta_o^2 \, h\nu} \tag{12}$$

This differs from Eq. (9) in that the performance now varies as the square of the available power, and inversely as the square of the slant range r_o. (Range doesn't enter the dispersion-time limited performance at all.)

If the geometry is such that τ in Eq. (11) is less than τ_m, then Eq. (9) must be used. (This situation is not reached in Fig. 2.)

IV. ENGINEERING PARAMETERS FOR CALCULATING PERFORMANCE

We have taken the following as technical parameters in calculating possible link performance. In many cases, the state of the technology would not justify a closer estimate than the nearest factor of 10 (or $\pm$ 5 dB).

TABLE I: TECHNICAL PARAMETER ESTIMATES

1. Attenuation of Irradiance of Water to Depth (based on 100+ m of Jerlov[1] Type II water).. 30 dB

2. Underwater 45° cone acceptance angle filter bandwidth (based on $kT/h\nu$ for fractional bandwidth of colored glass or dyestuff).. 100 Å

3. Multipath Time Dispersion

   a. Through Water (based on general agreement)...................................... 10^{-7} sec

   b. Through Overcast Clouds (based on experiments and simulations of Bucher/Lerner[2]).......................... 10^{-4} sec

4. Sunlight at surface in blue-green window re 1 photon per m^2 (Appendix A)............................... 207 dB

5. Sunlight at surface in 100 Å re 1 photon/sec-m^2....................................... 194 dB

6. Full sun/Full moon... 50 dB

7. Dark night skyglow in blue-green re 1 photon/m^2 sec (based on 1 Rayleigh per Å over roughly 1000 Å)........................... 120 dB

8. Dark night skyglow in 100 Å band re 1 photon/m^2 sec...................................... 110 dB

9. Conversion efficiency, sunlight to laser signal (based on 10% conversion of sunlight to conditioned power and 1% d.c.-to-green light laboratory results)............................. 0.001

In addition to the above, a calculation of potential link performance requires some entries which are partly matters of engineering judgement. These are

TABLE II: ENGINEERING PARAMETERS

Area of Receiver Aperture........................... 1 m^2

Engineering Performance Margins
(Reflection, efficiency, system).................... 25 dB

Bits per symbol..................................... 1

I believe the selection of 1 m^2 to be optimistic, but possible. The
factor A_R enters as the square root in Eq. (8), so that modest changes to
some more realistic aperture would not grossly affect performance.

Engineering margins are the price exacted by a recalcitrant nature for
systems that work. They include the margins needed to overcome various
receiver inefficiencies, to assure reliable signal detection, to allow for
slant-angle and other signal fading, and for other uncertainties in the
transmission model; and to allow for degradation in the satellite components.
When the technology is not well-developed and the idiosyncracies of the
channel not well-known, 30 dB is a conservative rule-of-thumb for these
margins. The 25 dB used here is possible because several factors enter only
as the square root.

Finally, when the signal consists of a sequence of low-duty-cycle pulses,
there is a temptation to try to transmit more than one bit per pulse, for
example, by using pulse position modulation. To do so would be unduly
optimistic. The technology is still too far from maturity to make credible
the squeezing of every possible bit from each dB of signal. In particular,
the most effective use of a pulse whose position can hop over an interval is
in providing AJ, not in providing additional bits. (For 10 bits of
alternative positions for a pulse, one can have 30 dB of AJ advantage.)

V.   DISCUSSION

Figure 2 raises the question, is any further effort for broadcast into the blue-green window warranted?

From the point of view of the system in which the link is embedded, it may not be necessary to work _through_ clouds on all occasions. From the point of view of the link, it may be possible to sense the location of small fractional cloud cover and direct a substantial fraction of the transmitter power to such specific areas. Thus, the limitations of cloud cover may not be critical.

The highest payoff would come from a technology that could support roughly 100W of blue-green light from the satellite. Such a technology advance would permit serious satellite design for nighttime only coverage from synchronous orbit. Although this is not really the place for such speculations, I would guess that the first sufficiently efficient forms of such sources would rely on intense fluorescence, but not lasing.

Eventually, I would expect that the 100 W of blue-green light could be obtained from a narrowband laser. Only then do I expect narrowband detection technology to pay off in the form of enough background noise reduction to raise the rate-area product to support a paging service in full sunlight. To do so will require effective source and filter bandwidths in the range of 0.1Å to 0.01Å in place of the 100Å assumed above. Again, this is not really the place for such speculations, but I would expect the noise-background-rejection technology to rely heavily on classical heterodyning with a local oscillator whose power output is also roughly 100 watts.

For the present, however, the purpose of the calculations carried out and discussed above and in the Appendices is the purpose stated in the introduction: to have a basis for evaluating the significance of technological realities and projections as they emerge in discussions with workers active in optical communication research.

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APPENDIX A

EFFECTIVE SOLAR POWER AT DEPTH

From Table XXI of Jerlov[1] and a value for the total sunlight at the surface in the band 0.3μ to 2.3μ of 900 W/m^2, we obtain the following table of total power transmitted to depth

TABLE A1

IRRADIANCE AT DEPTH, W/m^2

Depth in Meters	Water Type		
	Ib	II	III
0	900	900	900
50	16	6.3	0.37
75	3.8	1.1	0.016
100	0.9	0.2	0.0006*

---

*Extrapolated from 50 m and 75 m.

We can extrapolate the 75 and 100 m irradiances, linearly on a dB scale, back to the surface to find the total blue-green power at the surface that reached 100 m depth, as well as the effective attenuation suffered.

The result is given in Table A2.

TABLE A2: EFFECTIVE SURFACE POWER AND ATTENUATION

Parameter	Water Type		
	IB	II	III
Effective Extrapolated Surface Power	280 W	182 W	186 W
Effective Attenuation to 100 m Depth	25 dB	30 dB	55 dB

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Type II water is usually taken as the canonic water for the North Atlantic. Thus, 30 dB attenuation to depth is typical of Type II water for that portion of the solar spectrum which is effective at depth. The attenuation of the best-transmitted part of the spectrum in Type II water is also roughly 30 dB. Thus, we shall use the 30 dB in system calculations for both laser light and for the heliograph; even though the penetration in meters is slightly greater in the former case, if the operating wavelength has been well-chosen.

The 182 W equivalent surface flux is caused by one solar constant in space. Thus, if a heliograph were 100% efficient, there would be 135 W of useful light of the sea surface for every incident kw in space, allowing for some inefficiency of the heliograph mirrors in space, we have used 125 W per kw. Elsewhere (in Appendix C) we have arbitrarily used 21 dBW as blue-green power available at the sea surface for each m^2 of aperture in orbit; we have used 22 dBW m^2 at the sea surface, the corresponding interference from the sun.

REFERENCES

1. N. G. Jerlov, Optical Oceanography (Elsevier Publishing Co., New York, 1968).

2. E. A. Bucher and R. M. Lerner, papers in Appl. Opt., 12, 2381-2414 (1973).

APPENDIX B
PERFORMANCE EQUATION

In the text, Eq. (9) was given as

$$R\sigma_G \leq (W_D/Q) \sqrt{A_R \eta / P_N \, h\nu\tau_m} \qquad (B1)$$

We remarked that the role of Q could be expanded to include other margins; and the role of η, expanded to include transmission losses. We wish to make those remarks specific for use in the link calculations of Appendix C.

The receiver efficiency η was introduced as if it were a true efficiency. In fact, the receiver efficiency plays the role of a noise figure, in that we characterize any real receiver as having the same statistical performance as one with an aperture A_R and an overall efficiency η_R. This effective efficiency has the electron-output-to-photon input ratio as its upper bound.

Let us group this factor with Q. Further, instead of measuring W_D and P_N at depth, let us measure them high in the atmosphere, above the clouds, as W_o and P_{No}. If then t_a is the irradiance transmission of the atmosphere in the blue-green, and if t_w is that of the water (including the interface) we find

$$R\sigma_G \leq W_D \frac{\sqrt{\eta_R}}{Q} \sqrt{A_R \, t_a t_w / \rho_{No} \, h\nu\tau_m} \qquad (B2)$$

Strictly speaking, we should have used different transmissions for signal and interference, but the error is slight; it can be absorbed in the margin for the model. Now, the power output of the satellite degrades with time, and satellite optics darken with exposure. Thus, we must exact from W_o a satellite degradation factor m_s. On account of slant angle, the flux on the ocean is less than that calculated for normal incidence by a factor m_θ. On account of becoming dirty, the effective receiver area degrades with

time by a factor m_r. On account of unanticipated fading and oversimplification, the assumed irradiance transmission is optimistic by a factor m_p. Thus, we obtain for an actual system performance

$$R\sigma_G \leq \frac{W_o}{h\nu} \left[\frac{\sqrt{\eta_R/m_r m_p}}{m_s m_\theta Q} \right] \left[\sqrt{t_a t_w} \right] \sqrt{\frac{A_R h\nu}{P_{No} \tau_m}} \tag{B3}$$

The factors in the first bracket on the rhs of Eq. (B3) are the engineering performance margins, usually given as dB to be subtracted from total performance. The overall estimate of 25 dB for these margins is mainly a matter of experience. It could be justified as follows

Efficiency Margin.......$1/\sqrt{\eta_R}$..................... 5 dB

System Margin...........$m_s m_\theta \sqrt{m_r m_p}$............... 10 dB

Detection Margin.......Q........................ 10 dB

The reader ought not try to hassle individual dB's in this breakdown, which has been rounded off to the nearest 5 dB.

The next factor on the rhs of Eq. (B3) is $\sqrt{t_a t_w}$. The reciprocal, measured in dB, we shall call the loss margin. We have already assumed a standard 10^{-3} for t_w. For clear air, we shall assume t_a to be unity. (A dB or two actual attenuator is inconsequential on the scale of accuracy being evaluated here.) For overcast, we have already assumed t_a to be 1/10 of clear air. Thus, we find

Loss Margin.............$1/\sqrt{t_a t_w}$................. 15 dB clear air

20 dB cloud cover

APPENDIX C

PERFORMANCE

For $h\nu = 4 \times 10^{-19}$ Joule and 0.001 conversion efficiency, there are $(1.350)/(4 \times 10^{-19})$ photons per second of transmitter light per square meter of solar collector, A_T, or a transmitter power W_o

$$W_o = 185 \text{ dB re } 1 \text{ photon/sec} \qquad (C1)$$

For 185 watts/m^2 of blue-green light (at sea surface) redirected to the earth with 90% efficiency, we have for $w_o/A_T h\nu$

$$W_o = 206 \text{ dB re } 1 \text{ photon/sec} \qquad (C2)$$

For 185 watts of blue-green light at the surface, we have for $P_{No}/h\nu$

$$P_{No}/h\nu = 207 \text{ dB re } 1 \text{ photon/sec} \qquad (C3)$$

The rest of the factors used below are in Table I of the text.

Calculation 1a. Laser Source in Sunlight

		With Clouds	Without Clouds
1.	$W_o/A_T h\nu_2$ (Eq.(1)) for 1 m^2 solar collector (Eq.1)	185 dB ϕ/s	185 dB ϕ/s
2.	Performance Margin	25 dB	25 dB
3.	Loss Margin (from Appendix B)	20 dB	15 dB
4.	$P_{No}/h\nu$ (From Table I, #5	194 dB ϕ/m^{2}s	194 dB ϕ/m^{2}s
5.	τ_m (Table I, #3)	-40 dBs	-70 dBs
6.	N (add lines 4&5)	154 dB ϕ/m^2	124 dB ϕ/m^2

	With Clouds	Without Clouds
7. $\sqrt{N}/A_R$ (One-half line 6)	77 dB ϕ/m^2	62 dB ϕ/m^2
8. Total transmitter photons per decision (Add lines 2, 3 and 7)	122 dB ϕ/m^2	102 dB ϕ/m^2
9. Rate area product per m^2 of solar collector [subtract line 8 from line 1]	63 dB m^2/s	83 dB m^2/s

Calculation 2a. Laser Source with Full Moonlight

	With Clouds	Without Clouds
10. Diminish N by Line 6 of Table I, ratio of sun to moon	50 dB	50 dB
11. Hence, increase performance by one-half of line 10	25 dB	25 dB
12. Rate-area product per m^2 of solar collector (add line 11 to line 9)	88 dB	108 dB

Calculation 3a. Laser Source on Dark Night

	With Clouds	Without Clouds
13. Skyglow in dark (Table I)	110 dB $\phi/m^2 s$	110 dB $\phi/m^2 s$
14. Ratio of sunlight to skyglow (subtract line 13 from line 4)	84 dB	84 dB
15. Hence, increase performance by 1/2 line 14	42 dB	42 dB
16. Rate-area product per m^2 of solar collector [add lines 9 and 15]	105 dB m^2/s	125 dB m^2/s

Calculation 1b. Heliograph to Full Sunlight

	With Clouds	Without Clouds
17. $W_o/h\nu$ for $/m^2$ satellite collector Eq. (C2)	206 dB ϕ/s	206 dB ϕ/s
18. $P_{No}/h\nu$ from Eq. (C3)	207 dB $\phi/m^2 s$	207 dB $\phi/m^2 s$

	With Clouds	Without Clouds
19. Ω_s	-40 dB sr	-40 dB sr
20. Add lines 18 and 19	167 dB ϕ/m^2s	167 dB ϕ/m^2s
21. Margins (add lines 2 & 3)	45 dB	40 dB
22. Square margins (double line 21)	90 dB	80 dB
23. Slant range to synchronous orbit	76 dBm	76 dBm
24. Slant Range Squared (Twice line 23)	152 dBm^2	152 dBm^2
25. (Photons)^2 per decision per m^2 of A_R; Add lines 20,22,24)	409 dB ϕ/m^2s	399 dB ϕ/m^2s
26. Rate area product per (sq m)^2 of solar collector. Twice line 17 minus line 25.	3 dB m^2/s	13 dB m^2/s

To scale to other solar collector areas, increase line 26 by 2 dB per dB of solar collector until one reaches the rates given below.

	With Clouds	Without Clouds
27. N for τ_m. Add lines 18 and 5	167 dB ϕ/m^2	137 dB ϕ/m^2
28. $\sqrt{N}/A_R$. One half line 27	84 dB/m^2	69 dB/m^2
29. Total photons per decision (add lines 22 and 27)	129 dB/m^2	109 dB/m^2
30. High Rate Region. Rate-area product per m^2 of solar collector subtract line 29 from line 17	77 dB m^2/s	97 dB m^2/s

Calculation 2b. Heliograph with Full Moonlight

	With Clouds	Without Clouds
31. Low rate region. Add line 26 and line 10	53 dB m^2/s	63 dB m^2/s

Increase these values 2 dB for each dB of satellite solar collector above 1m^2.

	With Clouds	Without Clouds

32. High rate region. Add
    line 30 and line 11 to
    obtain rate-area product
    per m^2 of solar collector

    102 dB m^2/s   122 dB m^2/s

Calculation 3b. Heliograph on Dark Night

33. Low rate region. Add line
    26 and line 14

    87 dB m^2/s   97 dB m^2/s

Increase these values 2 dB for each dB of satellite solar collector above 1m^2.

34. High rate region. Add line
    30 to line 15 to obtain
    rate-area product per m^2
    of solar collector

    119 dB m^2/s   139 dB m^2/s

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A link calculation is carried out to determine whether present blue-green technology can support wide-area broadcasting from satellite to oceanic underwater receivers at bit-per-second rates; and to determine what improvements, beyond the status of technology assumed, would be most productive in making such broadcasting possible. The link technology today is tens of dB away from supporting a wide-area broadcast service; the most productive direction for developmental technology is in producing a suitable, efficient laser source with one hundred watts or more of average power output.

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